

# Quantitative Protection Factors for Common Masks and Face Coverings

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Cite This: *Environ. Sci. Technol.* 2021, 55, 3136–3143



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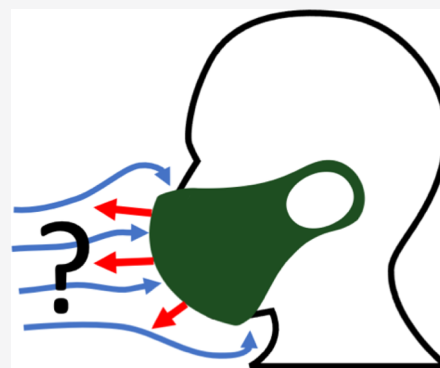


Article Recommendations



Supporting Information

**ABSTRACT:** The performance of masks, whether intended to protect the community from exhaled infectious aerosol or to protect the wearer from inhaled infectious aerosol, depends on factors such as filtration efficiency, particle size distribution, leakage, and ventilation rate. These factors depend on the activities and facial features of the mask wearer so that the mask performance for real-world applications is difficult to predict. The present work shows how protection factor, a quantity often used to describe mask performance, can be estimated without involving human volunteers. By constraining these factors to known values, mask protection factors can be compared fairly and efficiently following a series of filtration efficiency measurements performed in the laboratory. Protection factors and mask emissions for exhalation and inhalation were evaluated for masks of seven types currently in use around the world and for a hypothetical mask with 99% efficiency on all particles. The performance of reusable masks made from cotton fabric was limited by the size of the native cotton fibers. Masks that utilized finer fibers, particularly electret fibers with relatively small diameters, showed excellent performance with moderate flow resistance. Results from this work, in addition to simple guidance for mask fit and usage, can facilitate risk communication and decision-making efforts during the COVID-19 pandemic.



## INTRODUCTION

A common reason to wear a mask or a respirator has been to protect the wearer from inhaled airborne contaminants. Protocols to evaluate mask performance for this purpose have been developed,<sup>1–3</sup> and standards are in place that specify the performance necessary to protect mask wearers from airborne contaminants in the workplace.<sup>4</sup>

During the coronavirus pandemic, masks primarily serve a different purpose: they help protect the community from infective droplets that a wearer might exhale.<sup>5</sup> This purpose forms the primary rationale for wearing masks in public places,<sup>6</sup> though masks also protect the wearer from inhaled infectious aerosols. Standards have not been developed to evaluate how well masks perform to achieve this second purpose although some guidance is available.<sup>7,8</sup> At the same time, individuals and companies are producing homemade and manufactured masks intended to collect exhaled particles and droplets. Those making homemade masks may have little information about which mask materials are most effective. Purchased masks intended to protect the community often come without information about the level of protection they provide. As a result, there is much confusion about the relative protection that any given mask affords the wearer.

Many factors affect mask performance, a term that includes both mask efficiency (the fraction of incoming droplets and particles it collects) and mask “breathability” (its pressure drop or resistance to flow). Masks often have multiple layers that work together to determine performance. For each layer,

factors such as fiber size and type, fabric structure, and fabric type may all be important.

Characteristics of the droplets and particles to be collected also affect mask efficiency, for example, collection efficiency can be poor for smaller droplets (i.e., those less than 1  $\mu\text{m}$  in aerodynamic diameter) but good for larger ones. Mask efficiency also depends on air velocity, which is proportional to air flow through the mask. Both droplet size distribution and flow depend on many factors, including whether the wearer is speaking and if so with what volume.<sup>9</sup>

Another determinant of mask performance is the extent to which exhaled or inhaled air bypasses the mask rather than flows through it. Bypass depends not only on mask construction (i.e., breathability) but also on how well the mask fits the wearer’s face; facial fit also depends on how effectively the wearer attaches the mask. Clearly, a mask worn over the mouth but not the nose or a mask worn around the neck that covers neither the nose nor mouth will provide limited or no protection regardless of how well the mask is designed and constructed.

**Received:** October 28, 2020

**Revised:** February 1, 2021

**Accepted:** February 2, 2021

**Published:** February 18, 2021



ACS Publications

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American Chemical Society

3136

<https://dx.doi.org/10.1021/acs.est.0c07291>  
*Environ. Sci. Technol.* 2021, 55, 3136–3143

The sizes and concentration of incoming droplets and particles, air flow through the mask, and bypass around it will likely differ during inhalation and exhalation so the same mask will provide different levels of protection to the community during exhalation and to the wearer during inhalation.

The interplay of community and wearer needs with mask characteristics and wearer behavior is complex. A need exists to combine the effects of all these factors into a single index of mask performance that is representative and fair, yet easily understood. We will utilize mask "Protection Factor," PF, to address this need. PF is commonly used to characterize the mask performance required to protect workers from hazardous airborne contaminants.<sup>4</sup>

This work has two objectives: (1) to develop a method to evaluate PF for masks used to protect both the community and the wearer that does not involve testing with mask-wearing participants and (2) to characterize a variety of masks currently in use around the world. Addressing these objectives requires identifying and evaluating factors that affect PF.

## PROTECTION FACTOR, PF

PF is the ratio of the contaminant concentration upstream of the mask,  $C_{in}$ , to the downstream concentration,  $C_{out}$ . Concentration is mass flow divided by air flow so that PF can also be understood as the mass flow of contaminants entering the mask,  $M_{in}$ , divided by that leaving the mask,  $M_{out}$ , as air flow through (or around) the mask is constant.

$$PF = C_{in}/C_{out} = M_{in}/M_{out} \quad (1)$$

For example, if PF is 5, then 1/5 of the incoming contaminant mass gets through; if PF is 10, then 1/10 gets through, etc.

The mask PF is usually employed to express how effectively a mask protects its wearer from an inhaled, hazardous material.<sup>4</sup> Tests can be conducted on individuals exposed to a nontoxic aerosol where the upstream concentration can be controlled and where the particle size is small enough to minimize problems with representative sampling.

Comparable PF tests to express how well a mask protects the community from exhaled aerosol would be much more difficult to conduct. Such tests would require upstream sampling inside a mask where the droplet concentration and the size distribution vary with activities such as speech.<sup>9</sup> Upstream concentrations vary substantially from person to person<sup>10–12</sup> and the relatively large droplets produced when speaking<sup>9</sup> would make them difficult to sample. These problems can be overcome if PF is expressed in way that allows upstream variables to be standardized. Doing so allows for the direct comparison of mask PF values without the need for human volunteers or the need to sample inside their masks.

## METHODS

**Speaking Versus Not Speaking.** A study of 10 healthy men suggests that while speaking one inhales with a quick breath at a relatively high flow, about 70 L min<sup>-1</sup>, and then exhales over a longer period at a lower flow, about 10 L min<sup>-1</sup>.<sup>13</sup> Since the volume of air inhaled and exhaled is the same, the fraction of time spent exhaling while speaking nonstop,  $F_{S,emax}$  for these flows is 70/(70 + 10) = 7/8. The corresponding fraction of time spent inhaling while speaking nonstop,  $F_{S,imax}$  is 1/8. These values will differ somewhat with

factors that include body height, weight, gender, and surface area.<sup>14</sup>

Droplets exhaled while speaking tend to be larger than those produced when not speaking and are generally lognormally distributed.<sup>15</sup> The count median diameter of these droplets is about 1 μm, with a geometric standard deviation of about 2.0.<sup>9</sup>

In contrast, while not speaking, one inhales at a more modest flow, approximately 15 L min<sup>-1</sup>, and then exhales at a flow of again about 10 L min<sup>-1</sup>.<sup>13</sup> For these flows, the fraction of time spent exhaling while not speaking,  $F_{N,emax}$  is 15/(15 + 10) = 3/5 and the corresponding fraction of time spent inhaling,  $F_{N,imax}$  is 2/5.

The droplets produced while not speaking are slightly multimodal, with a count median diameter of around 0.8 μm<sup>9,16</sup> and a geometric standard deviation of about 2.0. Count median diameters presented here<sup>9</sup> reflect only particles larger than about 0.5 μm, the limit of the instrument used in the measurement. The concentration of droplets produced while speaking,  $C_S$ , is about 10 times higher<sup>16</sup> than that produced when not speaking,  $C_N$ , although this factor varies greatly with the level of vocalization.<sup>9</sup> Perhaps surprisingly, the size distribution of droplets produced when vocalizing remains the same regardless of the level.<sup>9</sup> The size distribution measurements for dried exhaled particles generally indicate lower temperature and humidity conditions than those behind a mask and so may underestimate the droplet size exhaled. Results below are for droplets of the lung-lining fluid with 5% solid content,<sup>17–20</sup> results for their smaller, fully dried residuals<sup>9,16</sup> are shown in Figures S1 and S2 of the Supporting Information.

People speak only some of the time. If  $F_S$  is the fraction of time that one vocalizes, then the true fraction of time spent exhaling while speaking is the product of  $F_{S,emax}$  and  $F_S$  and the fraction of time spent exhaling while not speaking is the product of  $F_{N,emax}$  and (1- $F_S$ ). Similarly, the fraction of time spent inhaling while speaking is  $F_{S,imax} F_S$  and while not speaking is  $F_{N,imax} (1-F_S)$ . These times are important because the droplet size distribution, generation rate, and flow all change depending on whether one is speaking or not.

**Bypass.** Another factor that affects PF is the extent to which air flows around the mask rather than through it. Let  $B_{S,e}$  be the fraction of flow that bypasses the mask while speaking during exhalation,  $B_{N,e}$  be the fractional bypass while not speaking and exhaling, and  $B_{S,i}$  and  $B_{N,i}$  represent the corresponding bypass fractions during inhalation. Levels of bypass (quantitative "fit factors") have been reported for N95 respirators for particles around 0.08 μm, and they tend to vary from less than 0.1% to upward of 25% of the flow.<sup>21,22</sup>

Pan et al.<sup>23</sup> evaluated the effectiveness of cloth masks fitted to manikins during exhalation and inhalation at the same flows used here, 10 and 15 L min<sup>-1</sup> respectively. They report a sometimes sizeable decrease in inward and outward efficiency between a mask and its parent material and partly attribute this decrease to bypass caused by gaps between the mask and the manikin. For cloth masks made from flexible materials like the ones investigated here, this efficiency decrease ranged from minimal to about 50% for particles of the same size. These and other results with medical masks<sup>24</sup> suggest that bypass may range up to 50% for common face coverings. Surprisingly, Pan et al. found that the mask efficiency tended to be higher when exhaling than when inhaling; however, in most cases, the difference in these values was not large enough to be significant. If bypass largely determines the decrease in

Table 1. Base Case Conditions for Mask Evaluations<sup>9,13,16,21–23</sup>

parameter	conditions	value
fraction of time:	spent speaking, $F_S$	0.05
	relative concentration when:	
	speaking, $C_S$	10
	not speaking, $C_N$	1
maximum fraction of time inhaling:	speaking, $F_{S,i\max}$	1/8
	not speaking, $F_{N,i\max}$	2/5
maximum fraction of time exhaling:	speaking, $F_{S,e\max}$	7/8
	not speaking, $F_{N,e\max}$	3/5
bypass when:	speaking and exhaling, $B_{S,e}$	0.05
	not speaking and exhaling, $B_{N,e}$	0.05
	speaking and inhaling, $B_{S,i}$	0.05
	not speaking and inhaling, $B_{N,i}$	0.05
flow when:	speaking and exhaling, $Q_{S,e}$	10 L min <sup>-1</sup>
	not speaking and exhaling, $Q_{N,e}$	10 L min <sup>-1</sup>
	speaking and inhaling, $Q_{S,i}$	70 L min <sup>-1</sup>
	not speaking and inhaling, $Q_{N,i}$	15 L min <sup>-1</sup>
droplet $d_{50}$ and ( $\sigma_g$ ) when <sup>a</sup> : (log normal distributions)	speaking and exhaling	2.7 $\mu\text{m}$ (2) by count
		11.5 $\mu\text{m}$ (2) by mass
	not speaking and exhaling	2.2 $\mu\text{m}$ (2) by count
		9.2 $\mu\text{m}$ (2) by mass
	inhaling	0.2 $\mu\text{m}$ (2) by count
		0.8 $\mu\text{m}$ (2) by mass

<sup>a</sup>Based on solid content of 5%;  $d_{50}$  for dried particles when speaking = 1  $\mu\text{m}$ ,<sup>9</sup>  $d_{50}$  for dried particles when not speaking = 0.8  $\mu\text{m}$ ,<sup>9</sup>  $d_{50}$  = median aerodynamic diameter (by mass or count); and  $\sigma_g$  = geometric standard deviation.

efficiency between a mask and its parent material, these results suggest that  $B_{S,e}$ ,  $B_{S,i}$ ,  $B_{N,i}$ , and  $B_{N,e}$  have roughly similar values.

**Determination of PF.** With these concepts in mind, PF for exhalation through the mask can be determined from the sum of the generation rates for droplets produced when speaking and those produced when not speaking divided by the sum of the corresponding rates for droplets passing through the mask, including the effect of bypass

$$\begin{aligned} \text{PF} = & [C_S Q_{S,e} F_{S,e\max} F_S + C_N Q_{N,e} F_{N,e\max} (1 - F_S)] \\ & / [C_S Q_{S,e} F_{S,e\max} F_S (P_{S,e} (1 - B_{S,e}) + B_{S,e}) \\ & + C_N Q_{N,e} F_{N,e\max} ((1 - F_S)(P_{N,e} (1 - B_{N,e}) + B_{N,e}))] \end{aligned} \quad (2)$$

Here,  $P_{S,e}$  is the overall fractional penetration of droplets through the mask while speaking, which depends on the size frequency distribution of droplets produced while speaking,  $F_S(d)$ , and the mask fractional efficiency as a function of droplet size,  $\eta(d)$ , at the flow associated with exhalation while speaking

$$P_{S,e} = 1 - \int F_S(d) \eta(d) dd. \quad (3)$$

A similar relationship describes the overall fractional penetration of the droplets produced while not speaking,  $P_{N,e}$ .

The PF value for the mask when inhaling rather than exhaling can be determined in an analogous way by taking into account the differences in droplet or particle size distribution, in flow through the mask while speaking and not speaking, differences in penetration, which depends on both the particle size distribution and flow, and any differences in bypass.

In the special case where the mask wearer is not speaking and no bypass occurs, eq 2 can be simplified to  $\text{PF} = C_N / (C_N P_N)$  or  $1/P_N$ . In the same way that terms in the numerator and denominator of eq 2 address the effect of speaking on PF,

further terms could be added to address other issues such as level of physical activity.

We evaluated eight sets of masks, seven sets representative of different designs and constructions supplied by the World Health Organization and intended to represent mask design and use in different parts of the world. One mask in each of these seven sets was disassembled and examined with an optical microscope to determine its characteristics. Table S1 shows a photograph and provides measurements for masks of each type. For comparison, the performance of an eighth hypothetical “mask” was evaluated with its efficiency set to 99% for particles of all sizes (denoted as “M99”).

Masks A, B, C, and D employed two layers of cotton fabric and were intended to be washed and reused. The design and construction of masks A, B, C, and D were like those of some nonmanufactured masks. Masks E, F, and G were intended to be used once and then discarded. They were made from specialty materials and were commercially manufactured. Mask E was a KN95 respirator that replicated the performance of an N95 respirator. Mask F was intended for medical settings. The hypothetical mask M99 had 99% efficiency on particles of all sizes at all flows and served as a fixed basis for comparison.

“Base case” values for most variables in eq 2 were taken from the literature and are listed in Table 1. The relationship between the mask collection efficiency and the droplet diameter,  $\eta(d)$ , varies with the mask design and must be determined from experiments at each air flow of interest for both exhalation and inhalation. Exhaled air is at high humidity and flows through the mask in the opposite direction to inhaled air; the flow direction may affect the collection efficiency for multilayered filters.<sup>25</sup> Three masks in each of the seven sets were tested to determine the collection efficiency as a function of droplet diameter at each of the three flows listed in Table 1.

The method used to measure the mask collection efficiency is summarized here and is similar to that described



elsewhere.<sup>26,27</sup> Each mask fabric, including those pleated, was tested as a single flat layer and secured to one end of a cylinder with an 89 mm inside diameter using a ring clamp. This diameter exposed a mask area reasonably representative of that through which air passes when worn. A similar cylinder without a mask represented a no-mask condition.

Either cylinder could be mounted at the inlet of a vertical sampling column in a 0.7 m<sup>3</sup> aerosol chamber. A nebulizer (Micro Mist 1880, Hudson Respiratory Care Inc., Temecula, CA) in the chamber generated polydispersed droplets of a nonvolatile compressor oil with a density of 0.867 g/cm<sup>3</sup> (Ace Hardware Corp., Oak Brook, IL). The size distribution of this aerosol is shown in Figure S3. Clean air flowed through the chamber at a rate sufficient to keep the mist concentration constant. The chamber aerosol passed, in turn, through either the cylinder with the mask or the one without the mask and into this sampling column. An axially aligned probe at the bottom of the column led to an aerodynamic particle sizer (APS Model 3321, TSI Inc., Shoreview, MN) that sampled the column air at 5 L min<sup>-1</sup>. All mask tests used air flows above 5 L min<sup>-1</sup>; excess air left through a T below the sampling probe. Sampling columns with different diameters were used at different mask flows to keep the sampling isokinetic.

To determine the mask efficiency, two-minute samples were taken with and without the mask, with 1 min between, until six sample pairs had been obtained. For each pair, the mask efficiency,  $\eta(d)$ , for droplets of 42 sizes between about 0.5 and 12  $\mu\text{m}$  in diameter was determined as

$$\eta(d) = 1 - \frac{\text{counts with mask}}{\text{counts without mask}}. \quad (4)$$

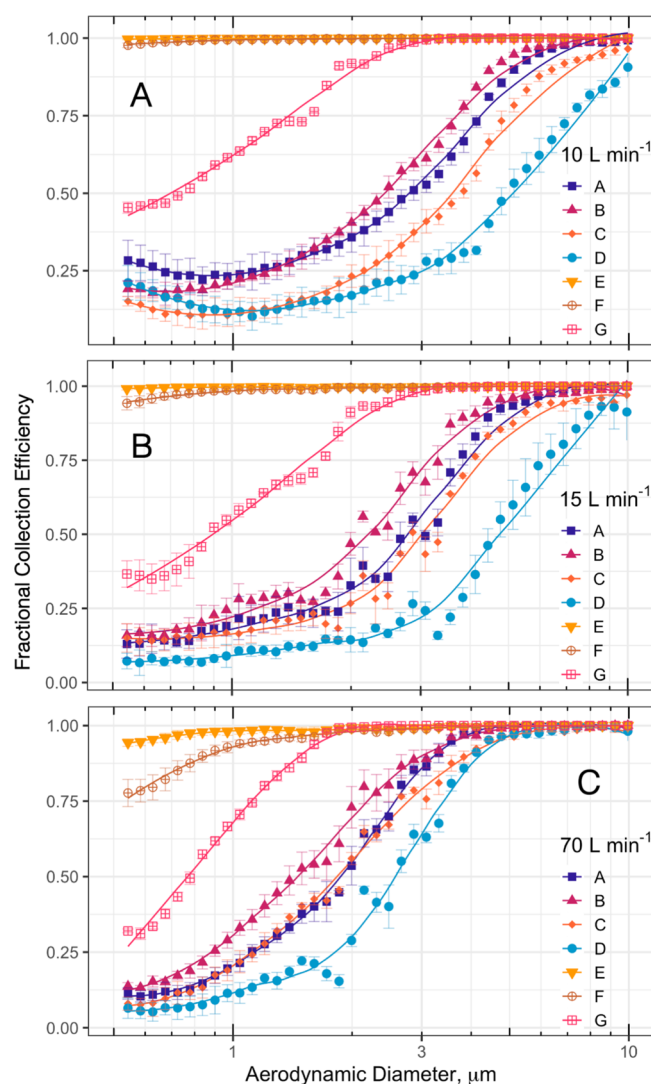
Measuring efficiencies in this way allows for cancellation of most sampling artifacts except for any related to concentration. Low droplet concentrations, below about 40 cm<sup>-3</sup>, were utilized to minimize coincidence errors in the APS. The resultant mass concentrations were about 200  $\mu\text{g}/\text{m}^3$ .

Efficiency was measured in this way with three masks for each of the seven mask sets. These measurements were made at each mask flow listed in Table 1, representative of speaking and nonspeaking and exhalation and inhalation. For the exhalation tests, chamber air was maintained at about 88% humidity, close to the maximum allowable limit in the APS, 90%. For exhalation tests, the masks were mounted backward to reflect the flow direction when the wearer exhales.

For each mask and for each air flow, a Magnehelic gauge (Dwyer, Michigan City, IN) measured the pressure drop through the mask using a tap on the side of the cylinder that held the mask.

## RESULTS

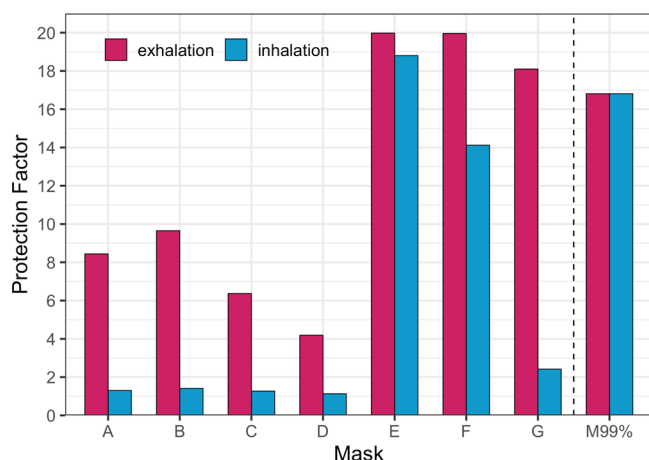
**Mask Collection Efficiency.** Figure 1 shows the measured collection efficiencies against droplet diameter at 10, 15, and 70 L min<sup>-1</sup> for each of the seven mask types. Error bars represent one standard deviation for differences in the performance of the three masks tested. At each flow, the results tend to cluster in the same way. For masks A, B, C, and D, the efficiency was relatively low for submicron particles but rose to higher values with the increasing particle size. Masks E and F had high efficiency for droplets of all sizes, and mask G had efficiencies between these two groups. For masks A, B, C, and D, the efficiency increased with velocity, consistent with collection by impaction. For masks E and F, the efficiency for small particles decreased with velocity, consistent with



**Figure 1.** Collection efficiency vs aerodynamic particle diameter for masks of seven types at flows of (A) 10 L min<sup>-1</sup>; (B) 15 L min<sup>-1</sup>; and (C) 70 L min<sup>-1</sup>.

collection due to diffusion or electrostatic attraction, for which collection decreases with less residence time. Figure 1 does not show data for the hypothetical mask M99%; its efficiency was constant and 99% for all particle sizes at all flows.

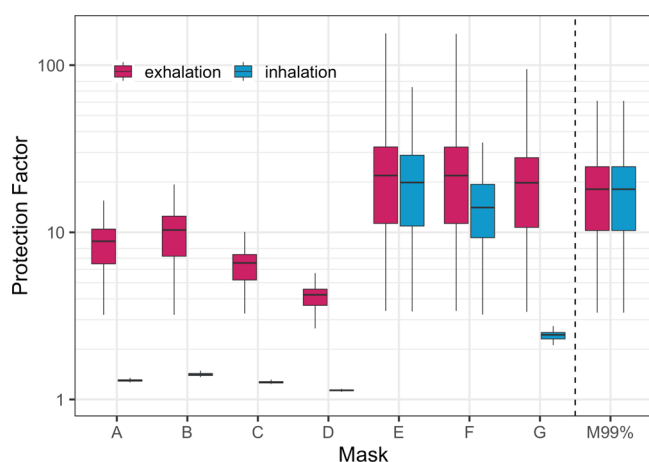
**Protection Factor.** Figure 2 shows the PF values obtained from eq 2 for the seven mask types utilizing “base case” conditions from Table 1, the collection efficiency data from Figure 1, and PF values for hypothetical mask M99%. Using common base case conditions allows for comparing the masks directly, though these values should not be taken to represent a typical person. For these conditions, masks A, B, C, and D provide reasonably good protection to the community from exhaled droplets as their PF values range from about 4 to 10. For these masks, the PF is largely determined by their moderate efficiencies for mid-sized particles as shown in Figure 1. Masks E and F provide much higher PF values, limited to 20 by the 5% bypass assumed for base case conditions. Mask G offers intermediate protection with a PF value of about 17. PF values for the hypothetical mask M99% were comparable to those of masks E and F. Figure 1 shows that mask efficiency generally increases with increasing droplet size and to the



**Figure 2.** PF at base conditions listed in Table 1 for seven mask types and for mask M99%.

extent that droplets behind a mask are larger than their fully dried residuals, PF values for exhalation would increase.

To investigate the causes of variability in mask performance, PF was evaluated for variability in the fraction of air that bypasses the mask,  $B$ ; in fraction of time when speaking,  $F_S$ ; and in relative concentration when speaking,  $C_S$ . A separate lognormal distribution represented the distribution of values for each of these factors with each mean set at its base case value listed in Table 1 and its geometric standard deviation set by values from the literature as described in the Supporting Information. Figures S4 and S5 show the variability in PF due to variability in each factor separately. Figure 3 shows the



**Figure 3.** Variability in PF caused by simultaneous variability in bypass, fraction of time speaking, and level of vocalization during exhalation and inhalation.

variability in PF due to the simultaneous variability in all three factors, for exhalation and inhalation. The ranges of PF shown in Figure 3 are perhaps representative of variability across a population of mask wearers, among whom factors such as bypass, time speaking, and level of vocalization would vary considerably from one person to another. These results suggest that mask effectiveness is likely to vary considerably among a population of users.

Figure 3 shows that masks A, B, C, and D provide fairly good protection to the community from exhaled droplets with PF values generally from about 4 to 10 although select instances

are substantially lower. These masks provide little protection to the wearer from inhaled droplets as their PF values are below about 1.5. Masks E and F provide much better protection to both the community and the wearer, with many PF values for exhalation above 20 and for inhalation generally above 10, although even these masks sometimes provide PF values below 4. Mask G provides good protection to the community with a PF value above 10 and modest protection to the wearer with a PF value of 2 to 3.

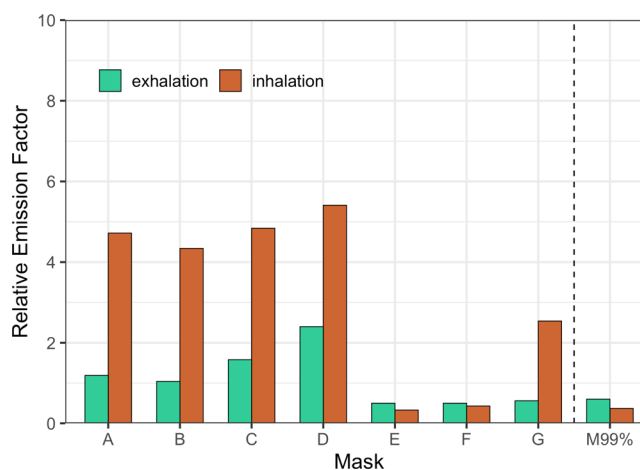
In all cases, the highest PF values for exhalation correspond to the lowest bypass. Figure S4 shows that the major cause of PF variability is variability in bypass, a factor that varies inversely with the fit and seal of the mask to the wearer's face. All masks collected the larger droplets produced when speaking with a higher efficiency, resulting in higher PF values. The hypothetical mask M99% had PF values much higher than those for masks A, B, C, and D but somewhat lower than those for masks E and F, which had very high efficiencies for particles of all sizes as shown in Figure 1.

A point of emphasis here is that all masks provide protection to both the community and the wearer. What differentiates the masks is the level of protection they provide, and that metric can be evaluated by comparing their PF values. From this standpoint, every mask is a good mask although some are better than others; however, even the best mask is of no value unless worn.

**Emissions.** Another important measure of mask performance is the mass emission rate of droplets through the mask, passing either into the community during exhalation or into the wearer during inhalation. The mass emission rate through a mask is given by the denominator of eq 2.

Emission rates through the different mask types tested here can be interpreted with the understanding that the quantities determined are relative and not absolute, that is, they allow comparisons between the masks but do not reflect absolute emissions. Thus, values for emission through the same mask during inhalation and exhalation cannot be directly compared.

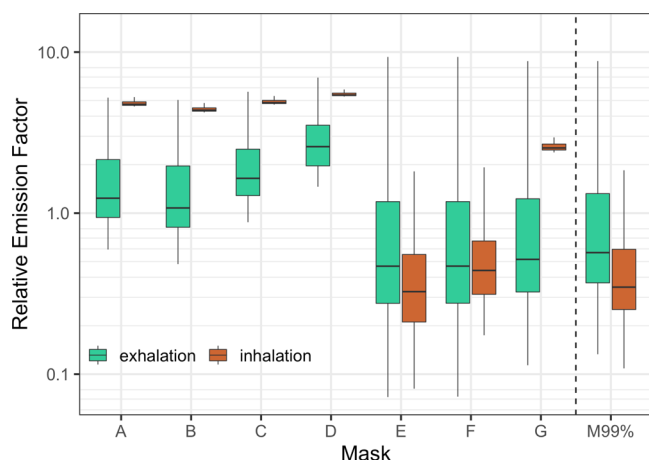
With this caveat, Figure 4 shows the comparison of the relative emissions through the seven mask types and through the hypothetical mask M99% for the base case conditions listed in Table 1. This figure shows that wearers of masks A, B, C, and D might pass from 6 to over 10 times as much exhalant to the community as wearers of masks E and F. Similarly,



**Figure 4.** Relative emissions at the base conditions listed in Table 1 for seven mask types and mask M99%.

masks A, B, C, and D allow more than 10 times as much to be inhaled compared to masks E and F. Exhaled emissions through the hypothetical mask M99% are much lower than those through masks A, B, C, and D and slightly higher than those through masks E and F.

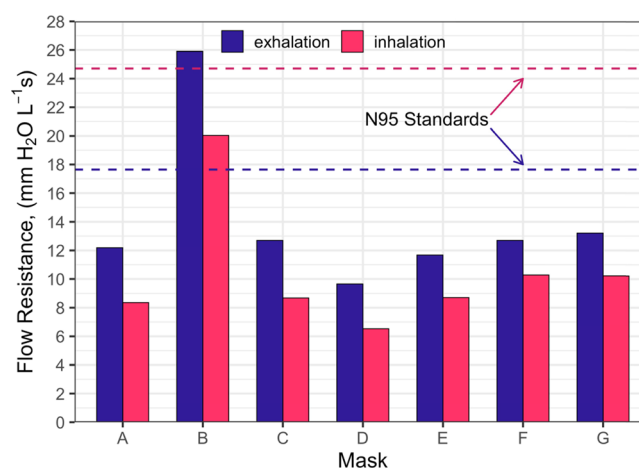
Figure 5 shows a box and whisker plot for emissions from the eight masks for the same simultaneous variability in bypass,



**Figure 5.** Variability in emission factor caused by simultaneous variability in bypass, fraction of time speaking, and level of vocalization during exhalation and inhalation.

fraction of time speaking, and level of vocalization used in Figure 3. Figures S6 and S7 show the variability in emissions due to each of these factors separately for exhalation and inhalation, respectively. Figure 5 shows that, in general, masks A, B, C, and D allow much more mass to be emitted to the community than masks E and F; however, for any given mask, possible emissions cover a broad range—particularly in the extremes where bypass reaches high values. Figure S6 shows that variability in bypass, speech, and level of vocalization are all important determinants of emission variability during exhalation for masks A, B, C, and D. Variability in bypass is most important for masks E, F, and G, which have higher efficiency and higher PF values. Emissions are higher when speaking, and even though PF increases with speech as well, this benefit is overwhelmed by the higher quantity of droplets the speaker produces.

**Breathability.** Figure 6 shows the flow resistance ( $\text{mm H}_2\text{O L}^{-1} \text{ s}$ ) for each of the seven mask types for exhalation ( $10 \text{ L min}^{-1}$ ) and inhalation ( $15$  and  $70 \text{ L min}^{-1}$ ) as well as the corresponding standards for N95 respirators ( $85 \text{ L min}^{-1}$ ).<sup>1</sup> Resistance was significantly higher for exhalation compared to inhalation for all masks ( $p < 0.01$ ) perhaps because the humidified air during exhalation tests affected the filtration media. The threshold for the detection of the inspiratory breathing resistance is about  $6$  to  $8 \text{ mm H}_2\text{O L}^{-1} \text{ s}$ ,<sup>28</sup> and Figure 6 shows that all masks had inhalation resistances close to or less than this value except for mask B. Resistances of all masks for both exhalation and inhalation were below the N95 standards except for exhalation through mask B. The European standard EN:149 for FFP2 masks<sup>3</sup> that are roughly equivalent to N95 calls for an exhalation resistance less than  $11.4 \text{ mm H}_2\text{O L}^{-1} \text{ s}$  at  $160 \text{ L min}^{-1}$  and inhalation resistances below  $14.2$  and  $15.4 \text{ mm H}_2\text{O L}^{-1} \text{ s}$  at  $30$  and  $95 \text{ L min}^{-1}$ , respectively. All masks except for mask B had resistances close



**Figure 6.** Resistance to flow for seven types of masks.

to this exhalation standard, and all masks met this inhalation standard except for mask B.

**Effect of Mask Construction on Performance.** The advantage of characterizing mask performance using PF is that by holding all environmental variables constant as shown in Figures 2 and 4, the effect of mask performance can be isolated. The interplay of droplet size distributions; air flow, direction, and properties; bypass; time spent speaking; level of vocalization; and mask properties affect PF and emissions in complex ways.

Some masks work better than others, and holding other variables constant, these performance differences must be related to differences in mask construction. Table S1 shows that masks A, B, C, and D all employed two layers of cotton fabric. Cotton fibers in these fabrics all had diameters from about  $12$  to  $20 \mu\text{m}$ . In masks A, B, and C, some cotton fibers protruded from their yarns into the pores at yarn intersections, undoubtedly aiding filtration. In contrast, the cotton yarn used in mask D had few protruding fibers. The relatively fiber-free pores in the mask D fabric may account for its lower efficiency and PF values.

Masks A and D each had an intermediate layer of spunbonded fabric with fiber diameters of about  $40 \mu\text{m}$ . An intermediate layer made from larger fibers than those in the surrounding cotton fabrics apparently collects few particles.

Masks E and F employed layers with synthetic fibers of  $2$  to  $7 \mu\text{m}$  in diameter, much smaller than the cotton fibers in masks A, B, C, and D. Furthermore, these layers displayed an electrostatic behavior and their fibers may have been electrets. Fine fibers with a permanent electrostatic charge could account for the high efficiency these masks achieved for particles of all sizes. Mask G employed fibers that were not quite as fine as those in masks E and F in layers that displayed no electrostatic behavior when handled. The collection efficiencies and PF values for Mask G were intermediate to those of the other two groups.

For masks A, B, C, and D that utilized cotton fabrics, comparison of Figures 3 and 6 shows that PF increased monotonically with flow resistance. These masks were relatively inefficient at collecting submicron droplets but had good efficiency for droplets larger than a few micrometers in diameter as shown in Figure 1. For these masks, most collection is probably due to impaction on fibers that extend into the pores at yarn intersections.



Masks E and F, which utilized small fibers that may have carried a permanent electrostatic charge, had PF values much higher than those for masks A, B, C, and D even though the flow resistance was about the same. Mask G achieved lower PF values than masks E and F at about the same flow resistance.

This work does not reflect the possibility that mask performance may change with use. Liquid droplets that a mask collects may draw fine fibers together due to surface tension, reducing the effective fiber diameter and decreasing the collection efficiency. In cold weather, the breath condensate may freeze, affecting the fiber size and shape. Condensation in the mask may increase the flow resistance by decreasing the porosity. Washing a cotton mask intended for reuse could increase or decrease the efficiency, depending on whether washing frees more fibers to extend into pore spaces or whether washing removes these fibers from the pores. Washing may also reduce the efficacy of electret fibers.

PF for a given mask undoubtedly varies from one wearer to another due to variability in many factors including variability in respiration and particularly flow bypass related to fit. The mask comparisons shown in Figures 2 and 4, based on fixed values for these factors, remove this variability to allow comparing masks on a common basis. The comparisons shown in Figures 3 and 5, based on variations in flow bypass, time spent speaking, and level of vocalization, suggest the ranges in mask performance that might result over a population of wearers.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.0c07291>.

High-resolution photographs and descriptions of the seven mask types with measurements of mask properties (Table S1); effect of upstream droplet diameter on protection factor and emission factor (Figures S1 and S2); size distribution for test aerosol (Figure S3); and variability during exhalation for PF and emission factor (Figures S4 and S5) and that during inhalation (Figures S6 and S7) (PDF).

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## Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

This work was supported by the World Health Organization, which also supplied the masks studied.

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